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Research article

Uncertainty analysis of the performance of a management system for achieving phosphorus load reduction to surface waters

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ABSTRACT

The recent re-eutrophication of Lake Erie suggests an inadequate phosphorus management system that results in excessive loads to the lake. In response, governments in Canada and the U.S. have issued a new policy objective: 40% reductions in total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads relative to 2008. The International Organization for Standardization (ISO) 31000 is a risk management standard. One of its analytical tools is the ISO 31010:2009 Bowtie Risk Analysis Tool, a tool that structures the cause-effect-impact pathway of risk but lacks the ability to capture the probability of reducing risk associated with different management systems. Here, we combined the Bowtie Risk Analysis Tool with a Bayesian belief network model to analyze the probability of different agricultural management systems of best management practices (BMPs) to achieve the 40% reductions in TP and DRP loads using different adoption rates. The commonly used soil conservation BMPs (e.g., reduced tillage) have a low probability of reducing TP and DRP to achieve the policy objective; while it can achieve the TP load reduction objective at increased adoptions rates >40%, it does not achieve the DRP load reduction objective, and in fact has the unintended consequence of increasing DRP loads. If decision makers continue to rely on soil conservation BMPs, the trade-offs between meeting objectives of different forms of phosphorus will require deciding whether the management priority is to achieve 40% load reduction objectives or to prevent further increases in DRP loads, the identified culprit causing the repeated algal blooms. In contrast, TP- and DRP-effective BMPS had higher probabilities of achieving the policy objective, especially at increased adoption rates >20%. The integration of Bayesian belief networks with the ISO risk management standard allows decision makers to determine the most probable outcomes of their management decisions, and to track and prepare for less probable outcomes, thereby decreasing the risk of failing to achieve policy objectives.

1. Introduction

Eutrophication has remerged as a problem in the western basin of Lake Erie, with nuisance algae again threatening ecosystem functions and associated services (Michalak et al., 2013; Scavia et al., 2014). The decline in Great Lakes ecosystem health triggered a bi-national agreement to manage environmental risks that led to the 1972 Great Lakes Water Quality Agreement (hereafter the Agreement) and a policy objective to limit the amount of phosphorus entering the lakes. A subsequent reduction of phosphorus loads to levels below the policy objective resulted in a “rapid and profound ecological response” in Lake Erie (Michalak et al., 2013), which was considered “one of humankind's greatest environmental success stories” (Matisoff and Ciborowski, 2005). However, the re-eutrophication of Lake Erie suggests that the ecosystem is changing such that the long-standing policy objective was no longer reliable for preventing eutrophication and related impacts. In response, governments from Canada and the United States once again mobilized to tackle the issue from a perspective that considers both total phosphorus (TP) and dissolved reactive phosphorus (DRP) management. The Annex 4 Nutrient Objectives and Targets Task Team (hereafter the Task Team) was assembled to recommend policy objectives for reducing the probability of Lake Erie cyanobacteria algal blooms. The Task Team recommended 40% reductions in TP and DRP loads relative to 2008 from all western Lake Erie basin tributaries and the Thames River (EPA, 2015). This reduction was recommended to achieve a 90% annual probability that cyanobacteria blooms in Lake Erie's western basin would be no larger than those observed in 2004 and 2012.

To achieve the policy objective, the performance of the management

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measures for reducing phosphorus loads needs to be analyzed and then improved. Agriculture and its contribution to non-point phosphorous loads to aquatic ecosystems can be managed by regulatory measures (i.e., the 2006 Nutrient Management Act) or voluntary measures (best management practices; BMPs). To measure the effectiveness of management measures comprised of BMPs, we need to know the percentages of phosphorus loads that are reduced by these BMPs. However, there is considerable variation in TP and DRP load reductions by individual BMPs (Dodd and Sharpley, 2016; Gitau et al., 2005; McElmurry et al., 2013). The broad ranges in BMP effectiveness for reducing phosphorus loads produce a considerable risk of failing to achieve the policy objective of 40% reductions in TP and DRP loads. Further, there is a potential for some BMPs to reduce TP but to increase DRP loads, thereby increasing the likelihood of eutrophication events. Without better predictions of anticipated BMP effectiveness prior to implementation, achieving the 40% reductions in TP and DRP loads in agricultural tributaries of the Great Lakes may be a "shot in the dark", with the potential to exasperate eutrophication risk and its impacts (Dodd and Sharpley, 2015; Sharpley et al., 2009; Smith et al., 2015). In order for western Lake Erie basin tributaries to achieve 40% reductions in TP and DRP loads while reducing the uncertainty of unintended consequences, simple tools are needed that can identify strengths and weaknesses as well as gaps and redundancies in the management systems.

Creed et al. (2016) introduced the use of the International Organization for Standardization (ISO) 31000 Risk Management Standard and the ISO 31010:2009 Bowtie Risk Analysis Tool for understanding the risk in reducing phosphorus loads to the Great Lakes. However, the Bowtie Risk Analysis Tool lacks the ability to estimate the uncertainty in the effectiveness of the management measures used to reduce the risk. Bayesian belief networks enable characterization of this uncertainty Cormier et al. (2018). Here, we illustrate the uncertainty in the performance of BMPs created by the distribution in the effectiveness and the

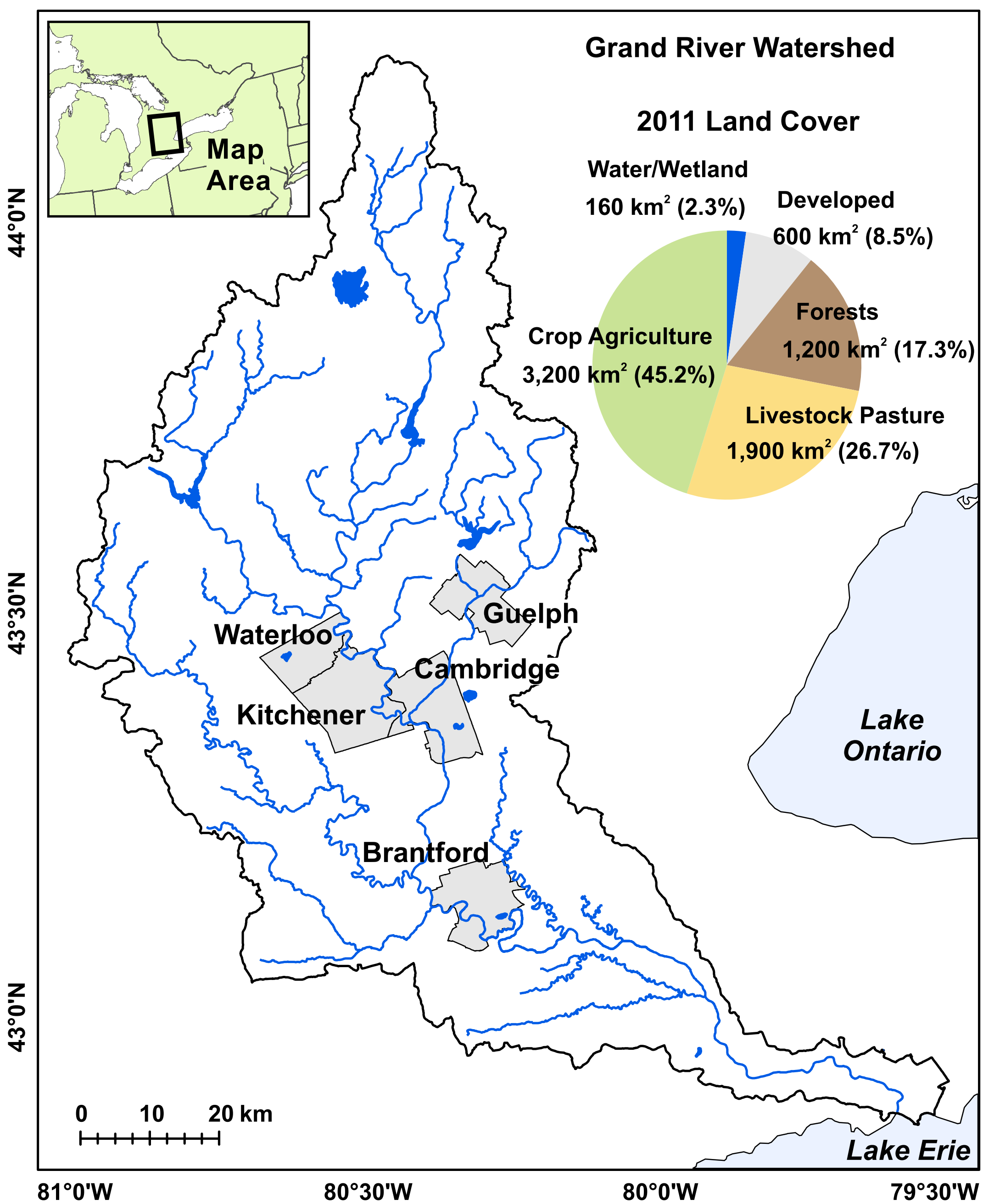

Fig. 1. Grand River watershed in southern Ontario and land cover in 2011 (data source: AAFC (Agriculture and Agri-Food Canada), 2013. Crop Mapping v3.).

variable adoption rates of BMPs. We (1) develop a Bowtie Risk Analysis Tool-inspired Bayesian belief network to simulate the probability of TP and DRP load reductions by BMPs, individually and collectively, and then (2) apply the Bayesian belief network to identify BMPs with the highest probability of achieving the policy objective of 40% TP and DRP load reductions from tributaries draining into Lake Erie. We hypothesized that increased adoption of commonly used soil conservation BMPs will be effective in achieving the targeted TP and DRP load reductions. We applied our Bowtie Analysis Tool using a Bayesian belief network to the Grand River watershed in southern Ontario, Canada, an agriculture-dominated watershed that, while it drains into the eastern basin of Lake Erie, had the data needed to develop and apply the tool. Recognizing that BMP effectiveness is context-dependent, the data that informed the distribution of BMP effectiveness included studies throughout the Great Lakes Basin and in north-eastern USA.

2. Material and methods

2.1. Test area

The Grand River watershed of Ontario drains 7120 km^2 of predominantly agriculturally land into Lake Erie's eastern basin. On an area basis, most of the Grand River watershed is crop (45.2%) and livestock (26.7%) land uses. Agriculture in the watershed operates on 6400 farms (Statistics Canada, 2006) representing 5100 km^2 (Lake Erie Source Protection Region Technical Team, 2008), divided almost evenly between livestock, crop, or combined operations (Fig. 1). The Grand River watershed discharged 447 metric tonnes of TP in 2008, including 407 metric tonnes of TP and 109 metric tonnes of DRP from agricultural sources (Maccoux et al., 2016). According to the Grand River Water Management Plan (2013), the three agricultural activities contributing phosphorus loads are mineral phosphorus application, manure phosphorus application, and livestock phosphorus losses (i.e., livestock fouling). As such, the Task Team identified the Grand River as a priority watershed for continual and enhanced management and monitoring of phosphorus loads.

2.2. Model structure

The ISO 31010:2009 Bowtie Risk Analysis Tool shows the risk pathway which includes drivers that create pressures, pressures that contribute to the risk and the prevention management measures which act to reduce these pressures, the risks that remain after the prevention management measures have been implemented, the impacts of these risks, and the mitigation management measures that act to reduce the severity of these impacts (Fig. 2).

The ISO 31010:2009 Bowtie Risk Analysis Tool was used to organize the risk pathway of agricultural phosphorus loads from the Grand River watershed to Lake Erie (Fig. 3). The drivers are agricultural activities that contribute phosphorus loads. The agricultural activities included mineral phosphorus application to crops, manure phosphorus application to crops, and livestock fouling, with each activity represented by a TP load node and a DRP load node in metric tonnes (Fig. 3). The prevention management measures to reduce these phosphorus loads to acceptable levels are on the left of the bowtie; the focus of this study. The prevention management measures were ten BMPs: three phosphorus source reduction BMPs (precision feeding of livestock, reduced phosphorus application rate to crops, and incorporated phosphorus application below the soil surface of cropland); four phosphorus transport reduction BMPs (reduced tillage that combined no-tillage and conservation tillage practices, crop rotation, winter cover crops, and contour cultivation); and three phosphorus sink enhancement BMPs (grass filter strips, forest filter strips, and wetlands). The prevention management measures include escalation factors that may undermine the effectiveness of BMPs; however, estimating the effect of escalation factors on phosphorus reduction by BMPs was beyond the scope of this study. The cumulative effects of agricultural activities are considered within the probabilities of achieving the policy objective (i.e., 40% reductions in TP and DRP loads from 2008 levels).

The performance of each BMP within the Bowtie Analysis Tool was estimated by Bayesian belief network (Fig. 3), where performance was a function of the effectiveness node (i.e., the proportion of phosphorus load reduced by the BMP) and the adoption node (i.e., the proportion

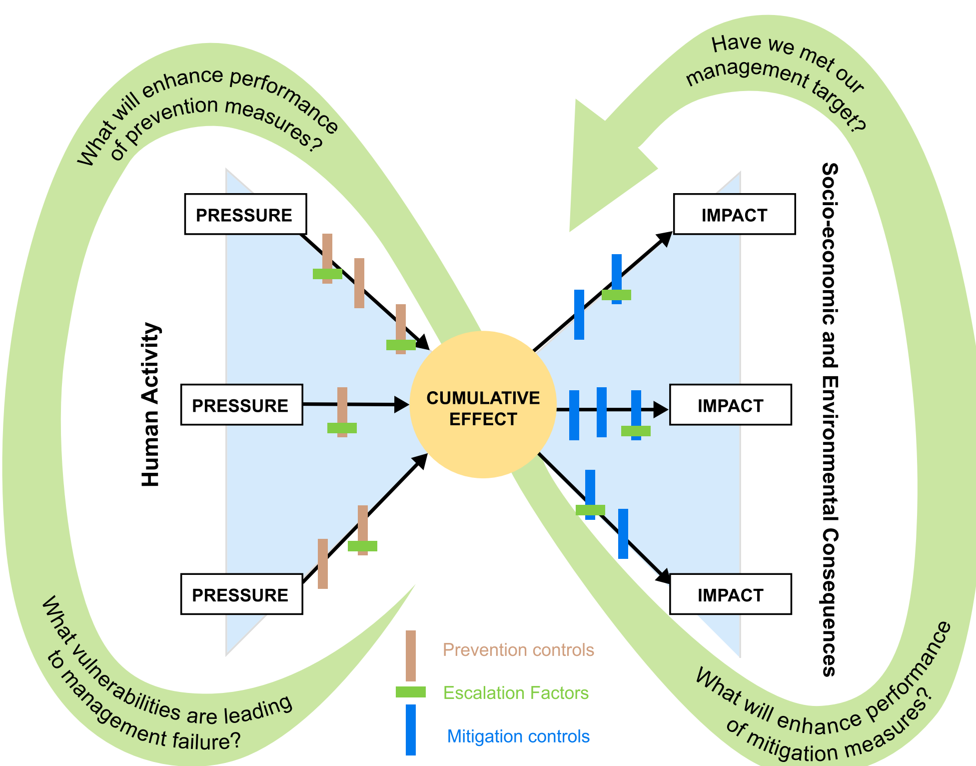

Fig. 2. The ISO 31010:2009 Bowtie Risk Analysis Tool analyzes the performance of management measures. Drivers are social, cultural, economic, and political factors that create pressures. Pressures contribute to the effect, and prevention management measures act to reduce these pressures. The effect is the risk event that results because of the residual pressures after implementing the prevention management measures. Environmental and socio-economic impacts occur because of the risk event. Mitigation management measures act to reduce the severity of these impacts. Escalation factors are outside influences that undermine the performance of prevention or mitigation measures (Creed et al., 2016).

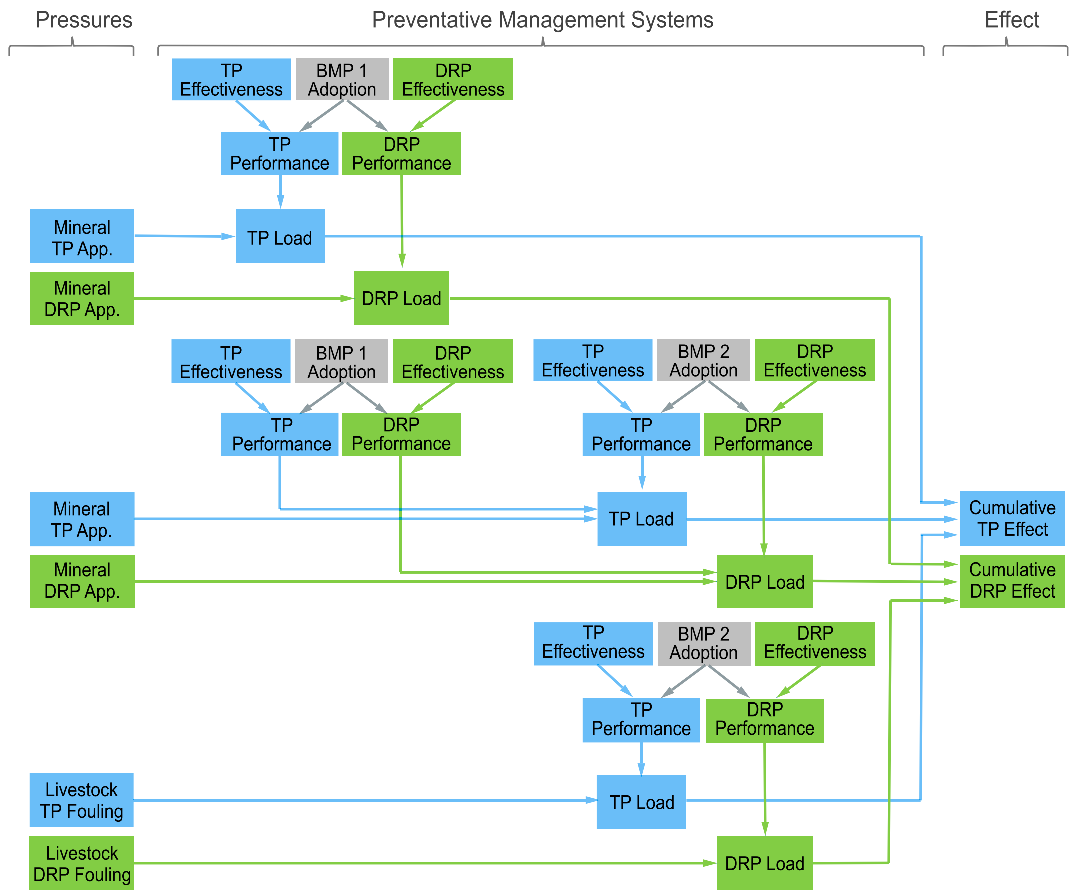

Fig. 3. Structure of the Bayesian belief network for the management of three agricultural activity pressures that contribute TP (blue) and DRP (green) loads to Lake Erie on the left, the influence of preventative BMPs in the middle, and the resulting residual TP and DRP risks on the right. Note: this is a conceptual diagram; the actual model developed between four and ten BMPs per pressure sequence. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

agricultural areas treated by the BMP) for each agricultural activity. Bayesian belief network sub-models included nine BMPs (all but precision feeding) for mineral phosphorus application, all ten BMPs for manure phosphorus application, and four BMPs (precision feeding, grass filter strips, forest filter strips, and wetland restoration) for livestock phosphorus losses. The Bayesian belief network sub-models were sequenced based on the position of the BMP along hydrological flow paths; this resulted in phosphorus source reduction BMPs first, followed by phosphorus transport reduction BMPs, and finally phosphorus sink enhancement BMPs.

The residual TP and DRP loads were the residuals of the 2008 TP and DRP loads that remained after reductions from the adoption of one or more BMPs for each agricultural activity. The cumulative effect was the sum of the residual TP and DRP loads for each of the three agricultural activities. The cumulative effects for TP and DRP were discretized into three states, representing 40–100% load reductions relative to 2008 (i.e., met the policy objective), 0–39% load reductions (i.e., short of the policy objective), and <0% load reductions (i.e., increased loads) (Fig. 3). The Bayesian belief network model was designed using Netica 6.05 for Bayes Nets software (Norsys Software Corp, 2018).

2.3. Model parameterization

2.3.1. Agricultural TP and DRP load nodes

The total TP and DRP load nodes were estimated using data from Maccoux et al. (2016), which reported annual TP loads from 2003 to 2013 and annual DRP loads from 2009 to 2013 from different tributaries to Lake Erie. To evaluate the performance of BMPs in meeting the policy objective of 40% reductions in TP and DRP loads from 2008 levels, we had to estimate the 2008 DRP load. The 2008 DRP load was estimated as the proportion of 2008 TP load equal to the average proportion of TP that was DRP from 2009 to 2013. Maccoux et al. (2016) also reported separate TP and DRP loads for municipal and industrial areas of the Grand River watershed. We assumed that the remaining load was contributed by agriculture areas that represented 80% of the Grand River watershed area (Grand River Conservation Authority, 2013).

TP and DRP loads were partitioned into separate mineral phosphorus application, manure phosphorus application, and livestock phosphorus loss loads to populate the three agricultural activities. Mineral TP and DRP application loads were calculated as the products of TP and DRP loads and the proportions of agricultural land in the Grand River watershed receiving mineral phosphorus applications (2006 Census of Agriculture (Statistics Canada, 2006)). Manure TP and DRP application loads were calculated as the products of TP and DRP loads and the proportions of agricultural land receiving manure phosphorus applications (2006 Census of Agriculture (Statistics Canada, 2006)) minus livestock TP and DRP loads from fouling. Livestock TP and DRP loads were estimated as the products of TP and DRP loads, the proportion of agricultural land receiving manure phosphorus application, and one minus the Ontario manure phosphorus recoverability coefficient (i.e., the proportion of phosphorus in livestock manure that is recovered from animal fouling and then available for application to cropland and pastures as fertilizer; the remainder is considered unrecoverable and therefore available for runoff; International Crop Nutrient Institute (2013)).

2.3.2. BMP effectiveness nodes

Effectiveness nodes for each BMP were estimated with distributions that estimated the probability of proportional reductions reported in published relevant studies (Table 1). Relevant studies from the Grand River watershed were limited; therefore, studies were compiled from the Great Lakes region and northeastern United States. Positive load reductions indicate load reductions, while negative load reductions indicate increases. Proportional load reductions were divided into bins or states, including five states with >0 reduction, five states with <0 reduction (if appropriate), and one state with 0 reduction (no effect; BMP had no further adoption). All distributions of proportional load reductions above and below 0 were tested for normality using the Wilk-Shapiro test ($p < 0.05$). For those distributions that passed the normality test, effectiveness distributions were generated as a normal distribution using the mean, standard deviation, maximum and minimum reductions reported in the literature. For those distributions that failed the normality test (precision feeding TP, reduced tillage TP, grass filter strips TP and DRP, and wetlands TP), distributions were generated using the "Learn from Cases" function in the Netica software, which calculates the true distribution of the compiled proportional load reduction values of each BMP. Effectiveness varied among BMPs and between TP and DRP proportional load reduction values. The BMPs appeared more effective for TP load reduction than for DRP load reduction: however, the differences between mean or median TP and DRP load reduction values were generally not significant.

Differences in the means of proportional TP and DRP load reductions were tested using two-tailed t-tests ($p < 0.1$) for BMPs where distributions of both proportional load reductions were normal (i.e., incorporated application, crop rotation, and contour cultivation). Differences in the medians of proportional TP and DRP load reductions were tested for all other BMPs using Mann-Whitney rank sum tests ($p < 0.1$).

Assumptions made in the parameterization of the Bayesian belief model and the potential implications of these assumptions are summarized in Table 2.

2.3.3. BMP adoption nodes

Adoption nodes for each BMP were estimated as distributions ranging from 0 to 1 indicating the proportion of agricultural areas that could be subjected to or treated by the BMP relative to the area subjected to or treated by the BMP in 2008. These proportions were discretized into five equal states >0 and one state = 0 (for modeling no increased adoption of the BMP). A proportion = 1 assumes that all agricultural area that was untreated by a BMP in 2008 could be subjected to treatment by that BMP. For wetland restoration, which is constrained by the ability of land to support restoration, this assumption does not hold. Here, the adoption node was equal to the total possible proportion of agricultural area that could adopt wetland restoration, which was calculated as follows. First, we generated a map of restorable wetlands assuming that tile drainage was the primary mechanism of wetland loss in the Grand River watershed; restorable wetlands were identified by intersecting a map of farm tile drainage (OMNRR, 2012) with a map of pre-settlement wetlands (ca. 1800; Ducks Unlimited, 2010) minus present-day wetlands (i.e., 2000–2015; Grand River Conservation Authority, 2015). Second, we generated a map of the contributing areas draining into each of the restorable wetlands. A hydrologically conditioned (Tarboton et al., 1991) 20-m digital elevation model (OMNR, 2011) was used to calculate the total contributing area as a proportion of the total agricultural area (AAFC, 2013) to each restorable wetland.

2.3.4. BMP performance nodes

The performance node refers to proportional reductions of TP and DRP loads by BMPs under increase adoption. A distribution of the performance for each BMP was generated in Netica by multiplying its effectiveness distribution by its adoption distribution, providing an estimate of its watershed-scale agricultural TP and DRP load reductions. The distribution of the performance resembles the effectiveness distribution when simulating 100% increased adoption (i.e., 1.0); on the other hand, when increased adoption is 0.0, performance is also 0.0, regardless of the BMP's effectiveness distribution. The first residual phosphorus load node reflects the initial load and the performance of the first BMP in reducing the phosphorus (P) loads (Eqn. (1)):

$$Load^{n=1}\left(PLoad, Performance^{n=1}\right) = \left(1 - Performance^{n=1}\right) \times PLoad \quad (1)$$

The probability distributions for all subsequent P loads nodes reflected the residual P loads preceding it and the performance of the specific BMP in reducing the P loads (Eqn. (2)):

$$P\,Load^{n}\left(PLoad^{n-1}, Performance^{n}\right) = \left(1 - Performance^{n}\right) \times PLoad^{n-1} \quad (2)$$

2.4. Model application

Four phosphorus reduction strategies were considered for their abilities to increase the probability of meeting the policy objective of 40% reductions in TP and DRP loads to Lake Erie compared to 2008 loads: (1) increased adoption of all BMPs; (2) increased adoption of commonly used (or promoted) BMPs; (3) increased adoption of BMPs effective for TP load reduction only; and (4) increased adoption of BMPs effective for DRP load reduction only (Table 3). The commonly used BMPs (e.g., soil conservation BMPs) were identified from Filson et al. (2009), Lamba et al. (2009), and the Canadian 2006 Census of Agriculture (Statistics Canada, 2006). TP-effective BMPs were BMPs that showed TP load reductions and no TP load increases in all studies used to derive the effectiveness nodes. DRP-effectiveness BMPs were those BMPs that showed no DRP load increases in the same studies.

To simulate increased adoption of BMPs in each management system, BMP adoption nodes were configured to reflect increased adoption rates relative to 2008 (i): (1) $0\% < i \leq 20\%$; (2) $20\% < i \leq 40\%$; (3) $40\% < i \leq 60\%$; (4) $60\% < i \leq 80\%$; and (5) $80\% < i \leq 100\%$. The increased adoption of BMPs not suitable to the respective management systems remained unchanged (i.e., 1.0 probability of 0% increased adoption). It is unrealistic to expect the adoption of all BMPs to increase relative to 2008, or at the same rate; however, more complicated scenarios with variable adoption probabilities were beyond the scope of the present study. We designated probabilities for each management system in each category of i of achieving ≥40% TP and DRP load reduction objectives ≥0.900 as highly probable, and ≥0.750 as probable.

3. Results

3.1. BMP management strategy effectiveness under increased adoption rates

As rates of BMP adoption relative to 2008 increased from 0 to 100%, the probabilities of meeting the TP and DRP policy objectives increased and therefore the risks of increased phosphorus loads decreased (Table 4).

3.1.1. Low increased adoption rates ($0\% < i \leq 20\%$)

At low increased adoption rates relative to 2008 ($0\% < i \leq 20\%$), the management system with all BMPs showed a high probability of achieving the ≥40% TP load reduction objective (0.913) but not the ≥40% DRP load reduction objective (0.292), and with a risk of increased DRP loads (0.344). The other management systems did not show a high probability (>90%) of achieving either the ≥40% TP or DRP load reduction objectives (Table 4). Therefore, at low increased adoption rates (0–20%), no management system met the criterion of a high probability of achieving both TP and DRP load reduction objectives.

3.1.2. Moderate increased adoption ($20\% < i \leq 40\%$)

At moderate increased adoption rates relative to 2008 ($20\% < i \leq 40\%$), three of four management systems showed high probabilities of achieving the ≥40% TP load reduction objective: all BMPs (0.999), TP-

Table 1

Descriptive statistics derived from experimental data, empirical equations, and expert opinion as captured from our literature review for proportional TP and DRP load reductions [0–1] by BMPs, and proportions of effectiveness [0–1] for ≤ 0%, >0%, >20%, >40%, >60, >80% load reductions. Significant differences (p < 0.1) in means or medians for individual BMPs are indicated in **bold**. Soil conservation BMPs are indicated by an asterisk. BMP effectiveness compilation sources are numbered and refer to the list of references below the table.

Best Management Practices		Proportional load reduction [0–1]						Proportion of load reduction effectiveness [0–1]						References
		Mean	Median	Max	Min	Range	95% Credible Interval	≤0%	>0%	>20%	>40%	>60%	>80%	
Precision feeding	TP	0.251	0.222	0.690	0.060	0.630	0.068–0.633	0.000	1.000	0.516	0.161	0.032	0.000	18,23,41,45,49
	DRP	0.181	0.177	0.344	0.110	0.234	0.113–0.302	0.000	1.000	0.200	0.000	0.000	0.000	
Reduced application	TP	0.536	0.490	0.765	0.365	0.400	0.377–0.746	0.000	1.000	1.000	0.800	0.300	0.000	10,11,43,47,48
	DRP	0.455	0.500	0.832	−0.024	0.856	0.027–0.804	0.077	0.923	0.846	0.615	0.231	0.077	
Incorporated application	TP	0.355	0.420	0.965	−0.187	1.152	−0.144–0.922	0.200	0.800	0.600	0.600	0.200	0.00	5,9,47,52
	DRP	0.660	0.679	0.975	0.053	0.922	0.133–0.954	0.000	1.000	0.909	0.818	0.727	0.364	
Reduced tillage*	TP	0.564	0.580	0.950	−0.220	1.170	−0.196–0.937	0.032	0.967	0.839	0.677	0.484	0.355	2,3,4,12,16,17,18,20,22,24,28,40,46
	DRP	−1.027	0.300	0.867	−4.100	4.967	−2.162–0.789	0.353	0.647	0.588	0.412	0.176	0.059	
Crop rotation	TP	0.753	0.728	0.980	0.534	0.446	0.550–0.964	0.000	1.000	1.000	1.000	0.750	0.375	11,12,21
	DRP	0.467	0.525	0.550	0.325	0.225	0.332–0.545	0.000	1.000	1.000	0.667	0.000	0.000	
Winter cover crops*	TP	0.620	0.480	0.940	0.286	0.654	0.307–0.920	0.000	1.000	1.000	0.800	0.400	0.400	4,18,26,38,42,53
	DRP	0.337	0.265	0.727	0.000	0.727	0.021–0.701	0.000	1.000	0.500	0.500	0.375	0.000	
Contour cultivation*	TP	0.446	0.370	0.930	0.080	0.850	0.106–0.881	0.000	1.000	0.792	0.458	0.250	0.125	12,16,21,22,36
	DRP	0.533	0.375	0.925	0.030	0.895	0.315–0.904	0.000	1.000	1.000	0.333	0.333	0.333	
Grass filter strips*	TP	0.578	0.552	0.950	0.104	0.846	0.190–0.933	0.000	1.000	0.978	0.731	0.452	0.194	1,6,7,8,13,14,15,16,17,22,29,30,31,33,37,44,51
	DRP	0.261	0.434	0.957	−2.580	3.537	−2.296–0.931	0.179	0.821	0.732	0.554	0.286	0.125	
Forest filter strips*	TP	0.651	0.694	0.976	0.300	0.676	0.324–0.954	0.000	1.000	1.000	0.778	0.556	0.444	15,29,31,36,39
	DRP	0.702	0.738	0.990	0.277	0.713	0.319–0.970	0.000	1.000	1.000	0.800	0.800	0.300	
Wetlands*	TP	0.414	0.310	0.980	−0.540	1.520	−0.486–0.958	0.133	0.867	0.500	0.433	0.367	0.200	9,16,22,25,27,34,50
	DRP	0.350	0.402	0.900	−0.270	1.170	−0.125–0.825	0.105	0.895	0.368	0.526	0.053	0.053	

1 Abu-Zreig et al. (2003)
2 Andraski et al. (1985)
3 Andraski et al. (2003)
4 Angle et al. (1984)
5 Baker and Laflen (1982)
6 Barfield et al. (1998)
7 Blanco-Canqui et al. (2004)
8 Boyer (2006)
9 Braskerud et al. (2005)
10 Bundy et al. (2001)
11 Burwell et al. (1975)
12 Chesapeake Bay Program (1987)
13 Daniels and Gilliam (1996)
14 Dillaha et al. (1989)
15 Doyle et al. (1977)
16 DPRA Inc. (1989)
17 Eghball et al. (2000)
18 Ghebremichael and Watzin (2010)
19 Ghebremichael et al. (2008)
20 Ginting et al. (1998)
21 Haith and Loehr (1979)
22 Hamlett and Epp (1994)
23 Hanrahan et al. (2009)
24 Hansen et al. (2000)
25 Jordan et al. (2003)
26 Klausner et al. (1974)
27 Kovacic et al. (2000)
28 Laflen and Tabatabai (1984)
29 Lee et al. (2003)
30 Lee et al. (1998)
31 Lee et al. (2000)
32 Lim et al. (1998)
33 Magett et al. (1989)
34 Mitsch et al. (1995)
35 Mostaghimi et al. (1988)
36 Novotny (1994)
37 Payer and Weil (1987)
38 Pesant et al. (1987)
39 Peterjohn and Correll (1984)
40 Phillips et al. (1993)
41 Pomar et al. (2011)
42 Reddy et al. (1978)
43 Schuman et al. (1973)
44 Schwer et al. (1989)
45 SERA 17 (2009)
46 Seta et al. (1993)
47 Tabbara (2003)
48 Westerman et al. (1985)
49 Wu, Z et al. (2000)
50 Yates and Prasher (2009)
51 Young et al. (1980)
52 Zhao et al. (2001a,b)
53 Zhu et al. (1989)

Table 2
The assumptions and their implications of data used to parameterize the Bayesian belief network model.

	Assumption	Implication
Agricultural TP and DRP load nodes	Data for the 2008 TP load to each of the three agricultural activities did not exist; we assumed the total load to the three agricultural activities was apportioned on an area basis.	The relative contribution of TP from different agricultural activities to the cumulative effect may not be accurate.
	The Ontario average manure phosphorus recoverability coefficient is directly applicable to the Grand River Watershed Livestock fouling load which is probably over estimated.	The proportion of initial TP load contributed by TP and DRP loads from manure application to crops and livestock fouling (which were estimated in part using Ontario's manure phosphorus recoverability coefficient) are likely under or over estimated as it is likely that the Grand River-specific manure phosphorus recoverability coefficient deviates from the Ontario average.
	Data of the relative proportion of DRP in the TP load for 2008 did not exist; we assumed it was the same as the relative proportion of DRP in the TP load for 2008.	We may have over or under-estimated the DRP load in 2008.
BMP effectiveness nodes	Data on the effectiveness coefficients for BMPs in the Grand River watershed were incomplete; we supplemented this information with data from other watersheds within the Great Lakes Basin as well as other watershed within north-eastern US.	The BMP effectiveness distributions used in the study are the best available but may not be representative of the Grand River watershed (future research need).
	BMP effectiveness data for TP reduction using crop rotation BMP were not available; we assumed the particulate phosphorus represented the dominant fraction of the TP load in crop systems.	Phosphorus load reduction may be over-estimated by the crop rotation BMP.
	BMP effectiveness data for TP and DRP reduction were limited for mineral and manure phosphorus reduction; we combined data and generated a single BMP effectiveness for manure and mineral phosphorus.	Phosphorus load reduction may be over-estimated for manure phosphorus and under-estimated for mineral phosphorus.
	BMP effectiveness data were generated from input/output loads or present/absent BMP studies. We assumed that the implemented BMPs intercepted 100% of farm runoff and therefore 100% of phosphorus load was treated (i.e., no phosphorus bypassed the BMPs).	BMP effectiveness may have been over-estimated, unless farmers implement BMPs to treat 100% of the hydrological flow path.
	We assumed that BMP performance is equal to Effectiveness*(Adoption), and if adoption = 1 (100%), then performance = effectiveness.	BMP performance would equal BMP effectiveness only if the BMP treated 100% of the hydrological flow path. BMP performance may over-estimate phosphorus load reductions in watershed discharge.
	We assumed that BMPs were implemented to spatially targeted to intercept the hydrological flowpath.	If BMP implementation is spatially random, then the effectiveness would be lower, especially at lower rates of adoption.

Table 3
Management options with selected BMPs. For each option, further adoption was simulated for the selected BMPs while adoption of unlisted BMPs remained unchanged or avoided.

Management System	Suitable Best Management Practices
All BMPs	Precision feeding, reduced application, incorporated application, reduced tillage, crop rotation, winter cover crops, contour cultivation, grass filter strips, forest filter strips, wetlands
Commonly used BMPs	Reduced application, reduced tillage, crop rotation, grass filter strips
TP-effective BMPs	Precision feeding, incorporated application, crop rotation, winter cover crops, contour cultivation, grass filter strips, forest filter strips
DRP-effective BMPs	Precision feeding, incorporated application, crop rotation, winter cover crops, contour cultivation, forest filter strips.

effective BMPs (0.994), and DRP-effective BMPs (0.936). At these increased adoption rates, the three management systems also showed higher probabilities of achieving the ≥40% DRP load reduction objective: all BMPs (0.760), TP-effective BMPs (0.840), and DRP-effective BMPs (0.866); each also showed low probabilities (≤0.087) of increased DRP loads. In contrast, moderate increased adoption of the management system with the commonly used BMPs showed a higher probability of achieving the ≥40% TP load reduction objective (0.822), but a low probability (0.105) of achieving the ≥40% DRP load reduction objective and a moderate probability of increased DRP loads (0.577) (Table 4). Therefore, at moderate increased adoption rates (20–40%), all BMPs, TP-effective BMPs, and DRP-effective BMPs met the criterion of a high probability of achieving both the TP and DRP load reduction objectives, but the commonly used BMPs did not.

3.1.3. High increased adoption ($i > 40\%$)

At high increased adoption rates ($i > 40\%$) relative to 2008, all four management systems showed high probabilities for achieving the ≥40% TP load reduction objective (1.000). At these increased adoption rates, three of four management systems also showed high probabilities of achieving the ≥40% DRP load reduction objective: all BMPs (≥0.961), TP-effective BMPs (≥0.982), and DRP-effective BMPs (≥0.999). Each of these management systems also showed low probabilities (≤0.016) of increased DRP loads. In contrast, high increased adoption of the management system with the commonly used BMPs showed a high probability of achieving the ≥40% TP load reduction objective (≥0.996), but a low probability of achieving the ≥40% DRP load reduction objective (i.e., 0.323 at $40\% < i \leq 60\%$, 0.504 at $60\% < i \leq 80\%$, and 0.641 at $i > 80\%$), and a continued risk of increased DRP loads (i.e., 0.385 at $40\% < i \leq 60\%$, 0.276 at $60\% < i \leq 80\%$, and 0.198 at $i > 80\%$) (Table 3). At high increased adoption rates, all BMPs, TP-effective BMPs, and DRP-effective BMPs met the criterion of a high probability of achieving both the TP and DRP load reduction objectives, but the commonly used BMPs did not.

3.2. Trade-offs between TP and DRP reduction objectives

At low increased adoption rates ($0\% < i \leq 20\%$), the management system with all BMPs showed the highest probability of achieving the ≥40% TP load reduction objective (0.913), but among the lowest probabilities of simultaneously achieving the ≥40% DRP load reduction objective (0.292). At low increased adoption rates, this management system had a low but not insubstantial probability of increasing the DRP load (0.344). Between the management systems based on TP- and DRP-effective BMPs, the TP-effective BMPs showed marginally higher probabilities of achieving both the ≥40% TP load reduction objective (0.715 compared to 0.430 for DRP-effective BMPs) and the ≥40% DRP load reduction objective (0.373 compared to 0.265 for DRP-effective BMPs) at low increased adoption rates. Both the TP- and DRP-effective BMPs

Table 4
Probabilities [0–1] of achieving ≥ 40% TP and DRP load reduction objectives, reductions short of objectives (0–39%), and increased loads (<0%) under different increased adoption rates relative to 2008 (i) for each BMP management system (≤20%: 0% < i ≤ 20%; ≤40%: 20% < i ≤ 40%; ≤60%: 40% < i ≤ 60%; ≤80%: 60% < i ≤ 80%; ≤100%: 80% < i ≤ 100%). Management systems that were highly probable (≥0.900) of achieving ≥ 40% reductions shown in **bold** with dark shading. Management systems that were probable (≥0.750) of achieving ≥ 40% reductions shown in **bold** with light shading.

Load Reduction (%)		All BMPs increased adoption rates					Commonly used BMPs increased adoption rates				
		≤20%	≤40%	≤60%	≤80%	≤100%	≤20%	≤40%	≤60%	≤80%	≤100%
TP	**≥40**	**0.913**	**0.999**	**1.000**	**1.000**	**1.000**	0.175	**0.822**	**0.996**	**1.000**	**1.000**
	0–39	0.087	0.001	0.000	0.000	0.000	0.825	0.178	0.004	0.000	0.000
	< 0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	95% Credible Interval	41–98%	41–99%	41–99%	41–99%	41–99%	1–64%	7–98%	41–98%	41–99%	42–99%
DRP	**≥40**	0.292	**0.760**	**0.961**	**0.991**	**0.998**	0.021	0.105	0.323	0.504	0.641
	0–39	0.346	0.153	0.023	0.005	0.0015	0.227	0.318	0.292	0.220	0.161
	< 0	0.344	0.087	0.016	0.004	<0.001	0.752	0.577	0.385	0.276	0.198
	95% Credible Interval	−1991-94%	−1477-98%	40–98%	41–99%	42–99%	−2015 -34%	−2008-74%	−1956-95%	−1906-97%	−1854-98%
Load Reduction(%)		**TP-effective BMPs increased adoption rates**					**DRP-effective BMPs increased adoption rates**				
		≤ 20%	**≤ 40%**	**≤ 60%**	**≤ 80%**	**≤ 100%**	**≤20%**	**≤ 40%**	**≤ 60%**	**≤ 80%**	**≤ 100%**
TP	**≥40**	0.715	**0.994**	**1.000**	**1.000**	**1.000**	0.430	**0.936**	**1.000**	**1.000**	**1.000**
	0–39	0.285	0.006	0.000	0.000	0.000	0.570	0.064	0.000	0.000	0.000
	< 0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	95% Credible Interval	41–98%	42–99%	42–99%	42–99%	42–99%	1–80%	13–98%	42–99%	42–99%	42–99%
DRP	**≥40**	0.373	**0.840**	**0.982**	**0.998**	**1.000**	0.265	**0.866**	**0.999**	**1.000**	**1.000**
	0–39	0.554	0.133	0.015	0.0018	0.000	0.735	0.134	0.001	0.000	0.000
	< 0	0.073	0.027	0.003	<0.001	0.000	0.000	0.000	0.000	0.000	0.000
	95% Credible Interval	1–98%	5–98%	42–99%	42–99%	42–99%	1–70%	15–98%	42–99%	42–99%	42–99%

showed low-to-zero probabilities of increased TP or DRP loads (≤0.073) at low increased adoption rates. The management system with the commonly used BMPs showed the lowest probabilities of achieving either the ≥40% TP (0.175) or the ≥40% DRP (0.021) load reduction objectives at low increased adoption rates, and also showed the highest probability of increased DRP loads (0.752).

At increased adoption rates (20% < i ≤ 40%), the trade-offs between achieving the ≥40% TP vs. the ≥40% DRP load reduction objectives effectively disappeared for three of the four management systems (all BMPs, TP-effective BMPs, and DRP-effective BMPs). The management system with the commonly used BMPs, however, continued to show a higher probability of achieving the ≥40% TP load reduction objective (0.822) than the ≥40% DRP (0.105) load reduction objective, and with the highest probability of increased DRP loads (0.577). At > 40% increased adoption rates, this pattern persisted for the management system with the commonly used BMPs, with an increasing probability of achieving the reduction objectives in TP loads (from 0.996 to 1.000) and DRP loads (from 0.323 to 0.641), and a decreasing probability of simultaneously increasing the DRP loads (0.577–0.198).

4. Discussion

With Lake Erie returning to a eutrophic state and threatening to compromise valued ecosystem services, Governments from Canada and the United States have mobilized to reduce TP and DRP loads from agricultural tributaries to the lake. Management of the agricultural phosphorus load in the Lake Erie basin has historically been driven by a focus on the reduction of TP loads, but this has been insufficient for preventing re-eutrophication and nuisance algae (Stumpf et al., 2012; Michalak et al., 2013). The Task Team recommended 40% reductions in TP and DRP loads relative to 2008 from all western basin tributaries and the Thames River that drain into Lake Erie (EPA, 2015). The adoption of risk management frameworks, such as the ISO 31000 Risk Management Standard, has been proposed to assess the risk of failing to achieve the 40% reductions in TP and DRP loads (Creed et al., 2016). Bayesian belief networks have been advocated for use within risk management frameworks (Cormier et al., 2018) to quantify the uncertainty in these risk assessments. Here, we developed and then applied the ISO 31010:2009 Bowtie Analysis Tool using a Bayesian belief network to show managers how to reduce the risk of failing to achieve the TP and DRP load reduction objectives by including uncertainty in the performance of management systems as determined by the adoption and effectiveness of BMPs.

4.1. Findings

By considering the uncertainty in the performance of BMPs being used to achieve the policy objective of 40% reductions in TP and DRP loads, we were able to reveal important findings. Namely, at low increased adoption rates, no management system had a high probability (90%) of achieving 40% reductions in both TP and DRP loads. At higher increased adoption rates, the TP- and DRP-effective management systems had high probabilities of achieving both the TP and DRP load reduction objectives, and therefore should be promoted. However, the commonly used BMPs had a high probability of achieving the 40% reduction in TP loads, a low probability of achieving the 40% reduction in DRP, and an unintended consequence of a moderate probability of increasing DRP loads, and therefore should not be promoted at any increased adoption rate.

4.2. Need for increasing adoption rates

To achieve both the TP and DRP load reduction objectives, managers should consider programs to increase adoption rates of BMPs. Currently, the likelihood of increased adoption rates is low (Kalcic et al., 2016). For increased adoption to be feasible, an understanding of the factors that influence farmers' decisions is required. In a survey of Ontario farmers by Statistics Canada (2011), the primary reasons for non-adoption of BMPs were economic pressures (54% of farmers), time required to implement and maintain BMPs (20.1%), lack of technical information on BMP function, implementation, and maintenance (9.3%), and other reasons (15.4%). For some farmers, financial incentives would increase adoption rates. Financial incentives and an appreciation and understanding of farmer personalities, motivations, business models, and influencing social circles is necessary to increase the engagement of farmers in protecting the Great Lakes and thereby to increase the likelihood of voluntary adoption of BMPs.

4.3. Need for shift from soil conservation to TP- and DRP -effective BMPs

Managers have relied on reduced tillage BMPs to achieve the TP load reduction targets (Coelho et al., 2012; Sharpley et al., 2012). Reduced tillage reduces the intensity, depth, and time of tillage to maximize productivity while reducing soil disturbance, thereby reducing particulate phosphorus loads (FAO, 2012). Voluntary implementation of reduced tillage resulted in a 75% reduction in TP loads and a 50% reduction in DRP loads from Lake Erie's largest agricultural tributaries, the Maumee and Sandusky Rivers (c.f. Dolan and Chaptra, 2012; Maccoux et al., 2016), between 1975 and 1995. However, after 1995, simultaneous with the peak adoption of the reduced tillage BMP, a substantial upward trend in DRP loads occurred while TP loads remained low (Richards and Baker, 2002; Sharpley et al., 2012). Some criticize that reduced tillage BMPs increased DRP loads (e.g., Laflan and Tabatabai, 1984; Gaynor and Findlay, 1995; Ghebrenichael and Watzin, 2010; Smith et al., 2015; Dodd and Sharpley, 2016) and contributed to the re-eutrophication of Lake Erie (Baker et al., 2014; Scavia et al., 2014). While reduced tillage limits soil erosion, it also reduces the incorporation of phosphorus fertilizers into the soil, thereby reducing the opportunity for phosphorus to sorb to sediments and instead to runoff as DRP in precipitation events (Dodd and Sharpley, 2014; Kleinman et al., 2011). Innovative BMPs specifically designed to manage legacy phosphorus with phosphorus sorption soil amendments have recently been advocated (Penn et al., 2007; Stoner et al., 2011; Qin et al., 2018); however, more research is needed to investigate the effectiveness of these phosphorus control structures.

Managers should consider increased promotion and adoption of TP- and DRP-effective BMPs to achieve the policy objective of 40% reductions in TP and DRP loads. Increased adoption of TP-effective BMPs at rates $\leq$20% created higher probabilities of achieving both TP and DRP load reduction objectives than adoption of DRP-effective BMPs at similar rates. While it may be expected that increased adoption of TP-effective BMPs could have adverse implications for DRP loads (Kleinman et al., 2015), the probabilities of increased DRP loads were low at all increased adoption rates. TP- and DRP-effective BMPs were equally effective in achieving TP and DRP load reduction objectives at adoption rates $>$20%, but with no difference in reducing the risk of elevated DRP loads. While increased adoption of DRP-effective BMPs was the only management option that was completely effective at avoiding increased DRP loads, the trade-off was lower probabilities of achieving TP load reduction objectives at increased adoption rates $\leq$40%.

4.4. Model assumptions

This study demonstrates the importance of increasing adoptions rates and shifting from "binary (yes or no)" to "probabilities" of the effectiveness of BMPs to inform setting of and achieving policy objectives. By integrating Bayesian belief networks into a risk management framework, managers are able to assess the risk of failing to achieve their policy objectives by determining the most probable outcomes of their management decisions, while tracking and preparing for less probable outcomes. However, to move this demonstration to practice, further data are needed. We had to make several model assumptions that may have led to an over- or under-estimation of the probabilities of reductions in TP and DRP loads. A lack of data was the main reason for the model assumptions, which required us to combine data, substitute data, and to broaden the geographic scope from where data were compiled.

Future research is needed to obtain these data and to include the incorporation of information on: (1) the effectiveness of BMPs under different contexts and under changing climatic conditions (e.g., a lack of relevant effectiveness data prevented us from including tile drainage in our analysis); (2) the lifespans of BMPs and the influence of BMP maintenance on BMP effectiveness; and (3) the proportion of agricultural runoff that is intercepted and treated by BMPs (e.g., a lack of spatially distributed data and models prevented us from tracking the movement of phosphorus within watersheds and therefore incorporating spatiotemporal dimensions into the effectiveness distributions for BMPs).

5. Conclusion

We face a high risk of failing to achieve the international policy objective of 40% reductions of total phosphorus (TP) and dissolved relative phosphorus (DRP) loads to reduce the probability of increased cyanobacteria algal blooms in Lake Erie. Our risk analysis of an agricultural tributary revealed that the continued use of soil conservation best management practices (BMPs) designed to reduce TP and DRP loads to surface waters may itself by a contributor to the re-eutrophication and harmful algal blooms in Lake Erie. Using a probability threshold of $>$90%, continued adoption of the no-tillage or reduced tillage BMP will be effective at achieving the $>$40% reduction in TP loads but only if adoption rates increase by $>$40%. At the same time, it will not be effective at achieving the $>$40% reduction in DRP loads; in fact, there is a substantial probability that it will increase DRP loads. In contrast, a shift towards TP- or DRP-effective BMPs will be effective, particularly at increased adoption rates $>$40%. Our risk analysis suggest that farmers should switch to BMPs that lower both the TP and DRP loads and be incentivized to increase their adoption rates.

CRediT authorship contribution statement

Jason D. Igras: Methodology, Writing - original draft, Investigation, Formal analysis. **Irena F. Creed:** Conceptualization, Methodology, Supervision, Resources, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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